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Space Administration

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California Institute of Technology
Pasadena, California

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Mission Level Autonomy for USSV

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ONR Unmanned Systems Program Review

Panama City, FL
27 JAN 2011

JPL Unmanned Maritime Tech Snapshot

• JPL has been under contract during the last 7 years with the US Navy, OSD, and commercial partners to transition flight-derived intelligent autonomy technology to unmanned surface and underwater boats.

• This technology has been demonstrated on-water in a number of high profile fleet level and NECC exercises including Trident Warrior 2009/2010 and Operational Adaptation DT01 & will be used in Trident Warrior 2011.

• Onboard intelligent autonomy that has been demoed on-water includes:

> high speed (> 25 knots) hazard detection/avoidance,

> resource-based mission-level planning/replanning,

> cooperative mission scenarios using multiple heterogeneous unmanned boats,

> onboard fusion and cross-cueing/interpretation of multi-modal sensory inputs for autonomous intercept and inspect operations,

> autonomous operations in close, highly cluttered harbor and riverine environments.
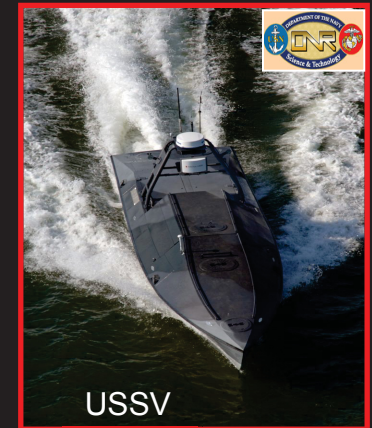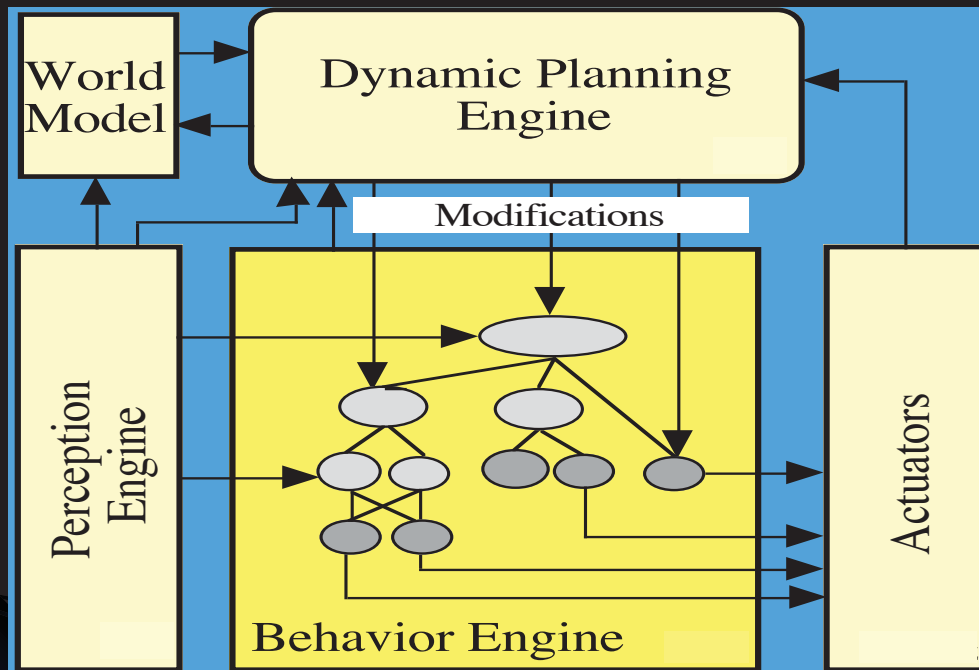
USSV

AMN1

CMV   7m RHIB

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Intelligent Autonomy Engine: CARACaS
(Control Architecture for Robotic Agent Command and Sensing)

World Model

Dynamic Planning Engine

Modifications

Perception Engine

Actuators

Behavior Engine

- CARACaS includes all required components of the Joint Architecture for Unmanned Systems (JAUS 3.2) Functional Agents (FA), Knowledge Stores (KS), and Device Groups (DG), and a subset of the non-required components.

- Behavior Engine [all JAUS Components of the Driver FA]

- Dynamic Planning Sub-Engine [JAUS Vehicle Commander Component of the Commander FA, and all Components of the BattleMap KS].

- Perception Engine [JAUS Objects of Interest Component of the Battlemap KS].

[Currently porting to JAUS 3.3]

- Control architecture with *reactive* processes for autonomous safe navigation and local path planning, *deliberative* processes for planning and reasoning about complex, possibly conflicting goals during mission operations, and *reflective* processes for resource management and self-preservation.

- Behavior Engine (based on CAMPOUT) with behavior coordination done using multiple-objective decision theory methods that guarantee a "good enough" or Pareto-optimal outcome.

- Dynamic Planning Engine (based on CASPER) uses iterative repair to guarantee update within specified time frame.

- Perception Engine (based on JPL Stereo) uses medium baseline stereo to provide dense range maps for hazard detection.
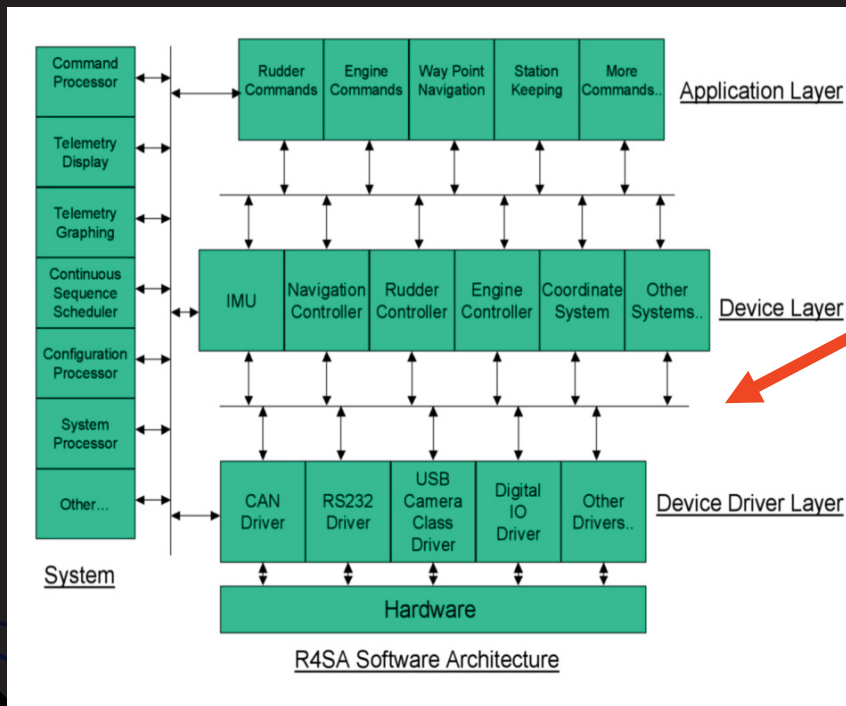
Cognitive Core

R4SA Software Architecture

- R4SA (Robust, Real-Time, Reconfigurable Robotics System Architecture) maintains the timing and synchronization between sub-system components.

Multi-Sensor Suite

Velodyne LIDAR
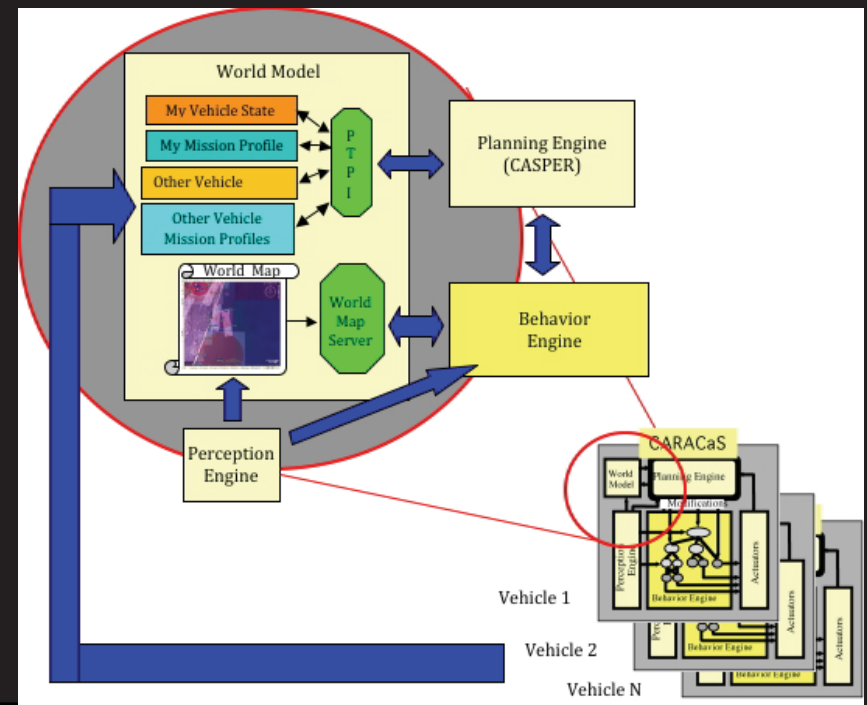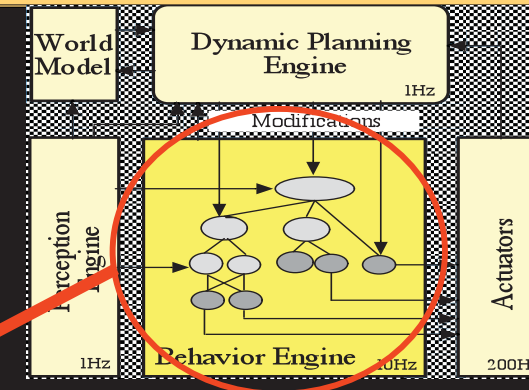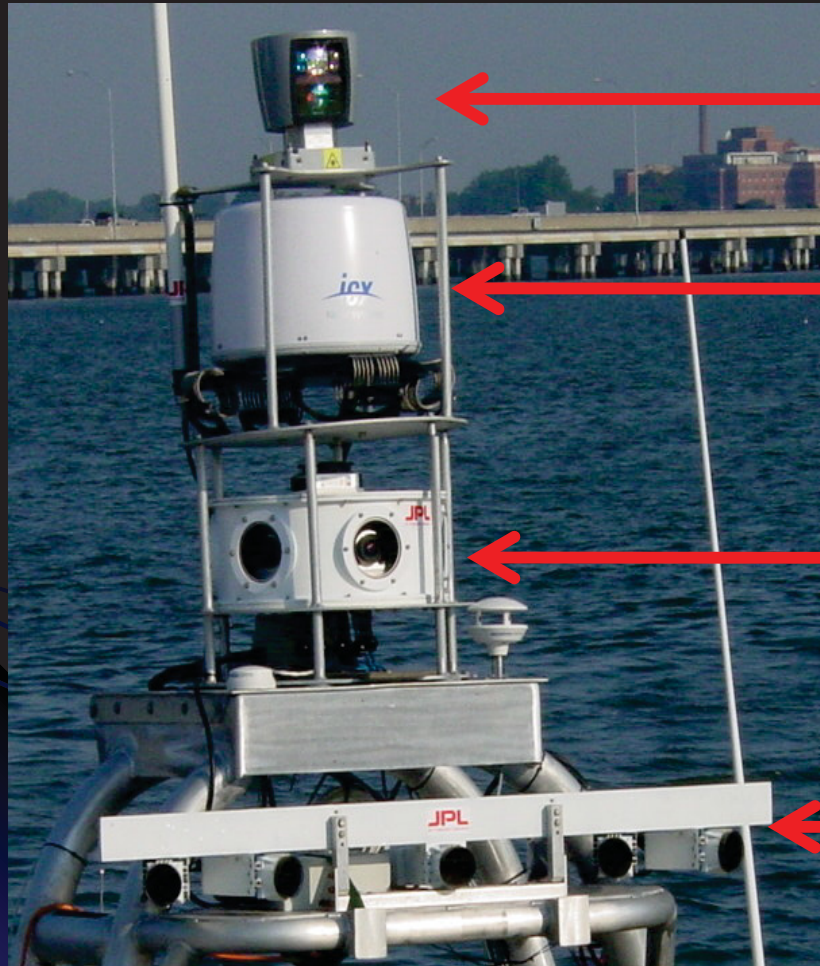
ICX Ka-Band Radar

JPL 360 Degree
Sensor Head

JPL Wide
Baseline Stereo

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JAUS
Interface Definition

USSV
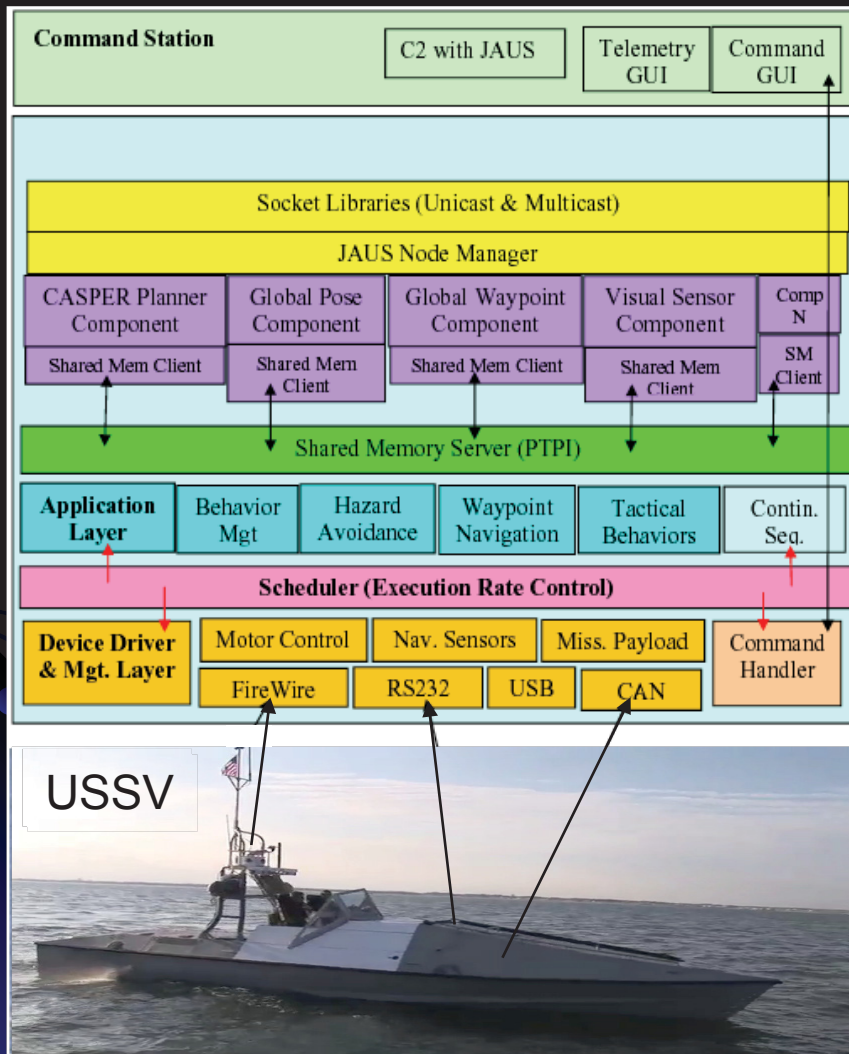
Subsystem & Component Discovery Sequence

Dynamic Configuration - Discovery process uses the client-server PTPI (Process-to-Process Interface) for the process of determining the existence of other components, nodes, and subsystems within the system, followed by Capability Publication to convey a component's capability to any other component within the system. These operations are done through the Node Manager.

Information is sent to C2 and other boats using the **MIEM (Maritime Infor. Exchange Model) XML schema format**

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

JPL CARACaS at a Glance

"Black box" intelligent autonomy system designed for optimal use of manpower based on years of experience in autonomous spacecraft operation

- **Open Architecture**, integrated blend of hard real-time and periodic process control using fully **POSIX conformal** QNX RTOS
- **Deterministic, modular system** with **Interface Control Documents (ICDs)** explicitly define the interactions / timing constraints between the sub-systems
- **Extensible command dictionary** with a **built-in sequence engine** for mission level tasking
- **Behavior-based control** for adaptive operations in dynamic environments coupled with an **onboard resource-based planner / replanner**
- **Distributed control** of multiple heterogeneous unmanned vehicles
- Single and multi processor communications through **PTPI (Process-to-Process Interface) and sockets** explicitly defined for interface and information sharing between hard real-time and periodic sub-system components
- Fee free licensing for government use (JPL is an FFRDC)

Resource-Based Planning for Goal Achievement

CASPER:
Continuous Planning/Execution

Capability

Generate and execute a detailed plan of action onboard the spacecraft. Quickly revise plan to accommodate:

- new objectives (e.g., new high-priority observation);
- hardware faults (switch to backup unit);
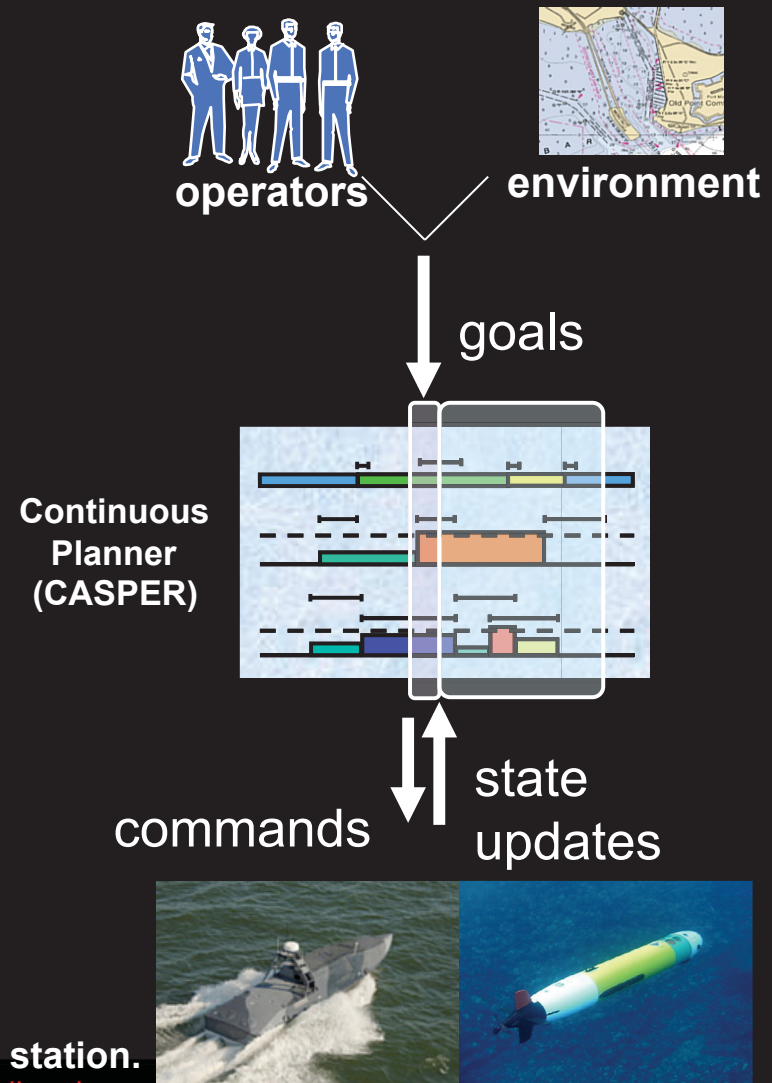- execution-time variations (e.g., resource usage, duration, outcome).

Advances over State-of-art

- **Continual update of plan during execution enables fast response to faults, opportunities, and changing goals.**
- **Fielded on flight processors.**

Maturity

- **Delivered for onboard operations of 3CS.**
- **Active on Earth Observing-1 satellite since Nov, 2004.**
- **Selected as NASA Software of the Year, 2005**
- **Lights-out automation of Deep Space Network ground station.**

operators   **environment**

goals

**Continuous
Planner
(CASPER)**

commands   state
updates

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```
//Volume of fuel stored onboard the
vehicle for use in running the engines
to provide thrust as well as onboard
power. Fuel is consumed according to
a lookup table appropriate for the
engine.
resource fuel_gal
{
  type = depletable;
  capacity = 300;
  default_value = 200;
  min_value = 0;
}
```

Constraint on USSV fuel capacity

```
survey survey_1 optional_goal
{
  priority              =      5;
  start_time            =     5m;
  duration              =    20m;
  target_latlon    = < 37.004721, -76.294508 >;
  target_extent_length_m  =  142.0;
  target_extent_width_m   =  445.0;
  target_extent_angle_deg =    0.0;
  max_speed_m_s           =    5.0;
  swath_width_m           =   75.0;
}
```
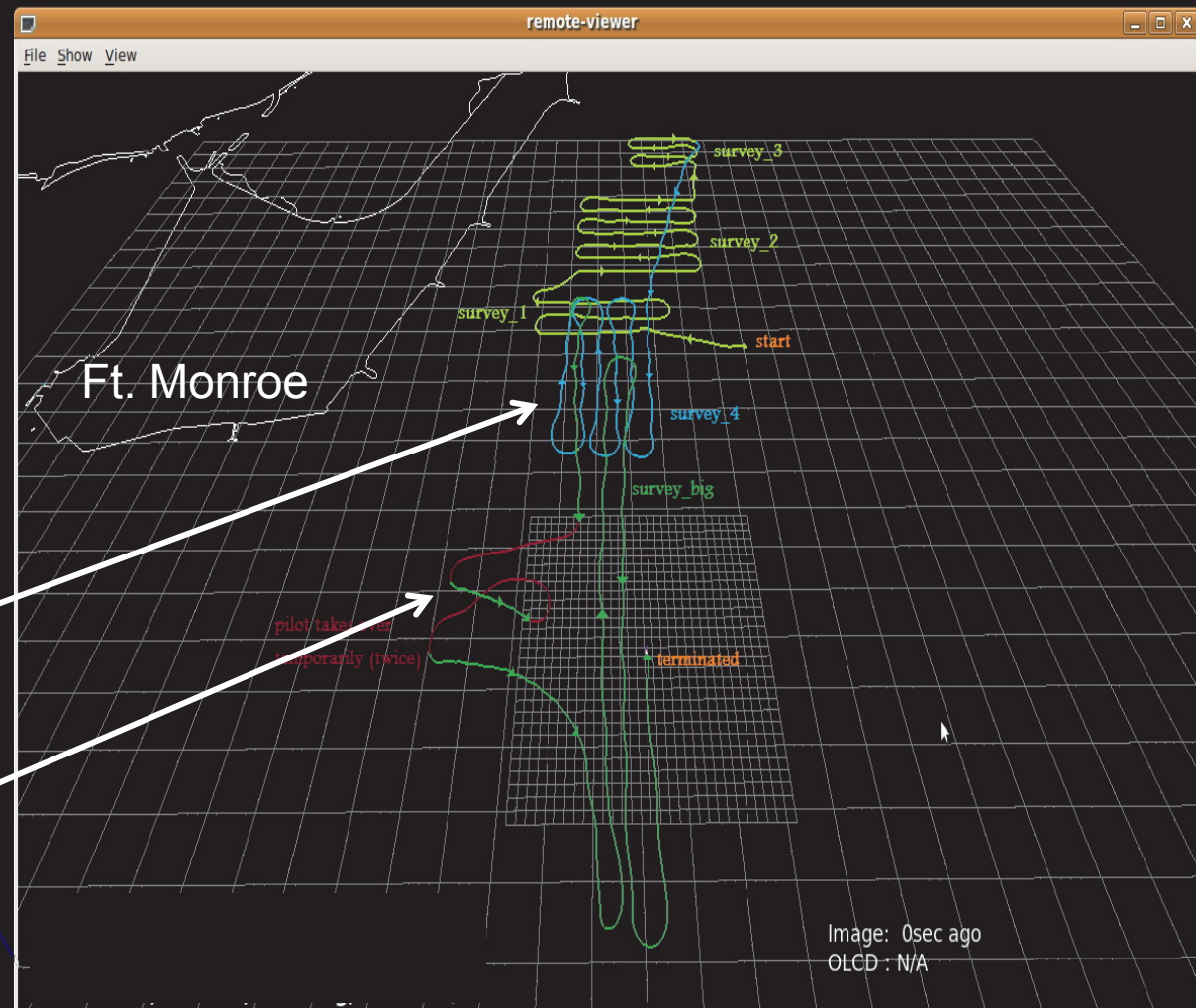
Area Survey Goal
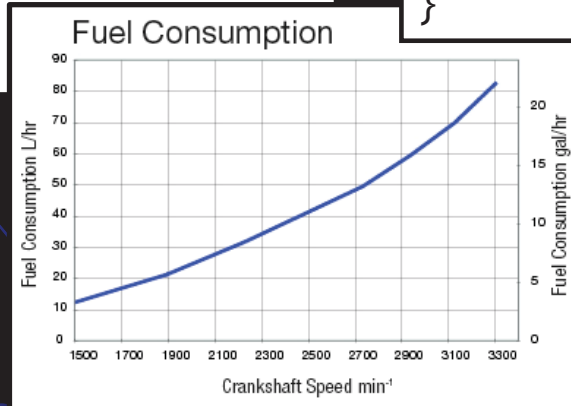
Fuel Consumption

Adaptive Area Survey

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- Successful on-water testing on the USSV at Norfolk, VA of **goal-based operations with resource management** tactical behaviors for adaptive area mine-sweeping.

- Autonomous coverage of multiple sweep areas with onboard resource monitoring and **dynamic replan** based on available mission time.

- **Sliding autonomy** demonstrated with seamless transitions between manual and fully autonomous control.
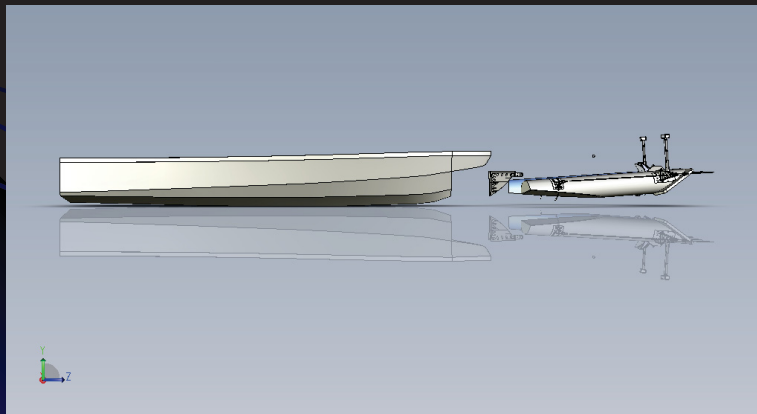
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Automated Retrieval:
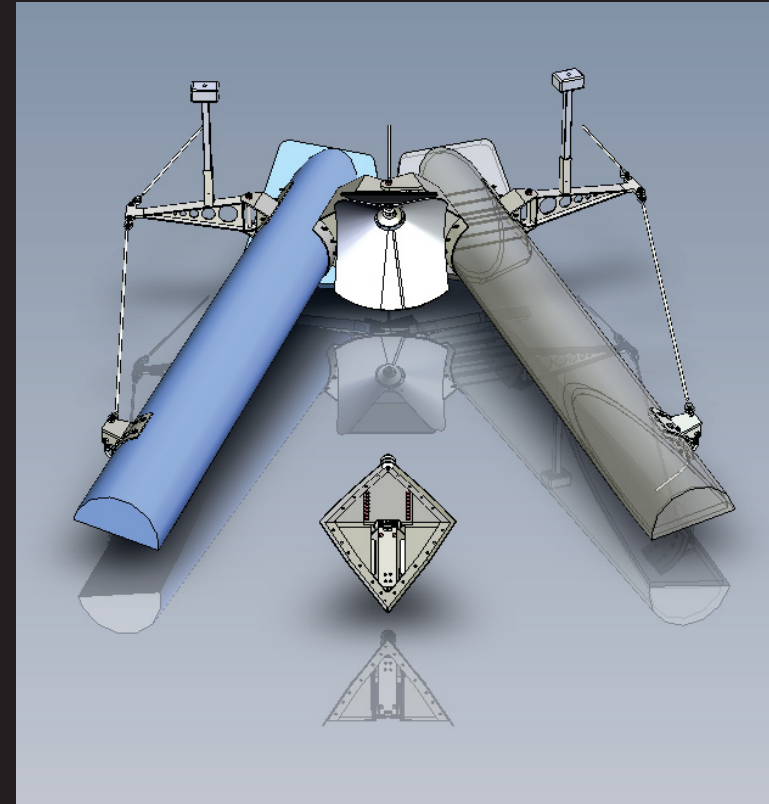# Sponson Docking

Sponson
(Docking/Retrieval Collar)
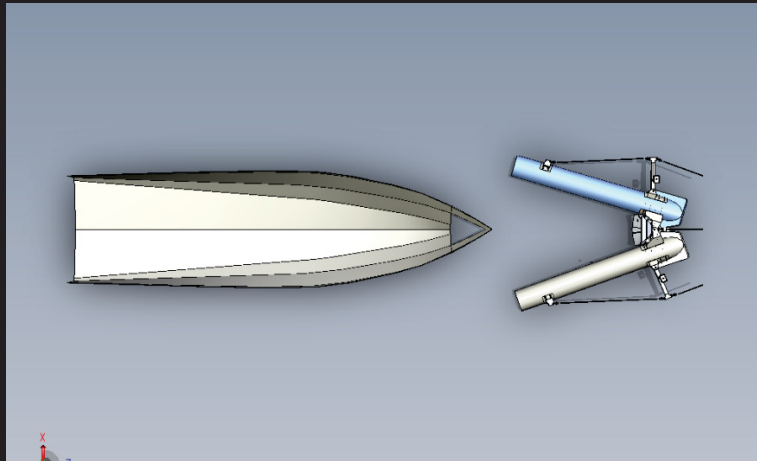
Top View

Side View

Docking

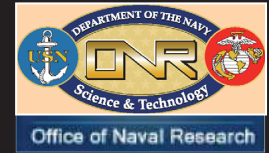Design of sponson was done by Carderock Combatant Craft Division

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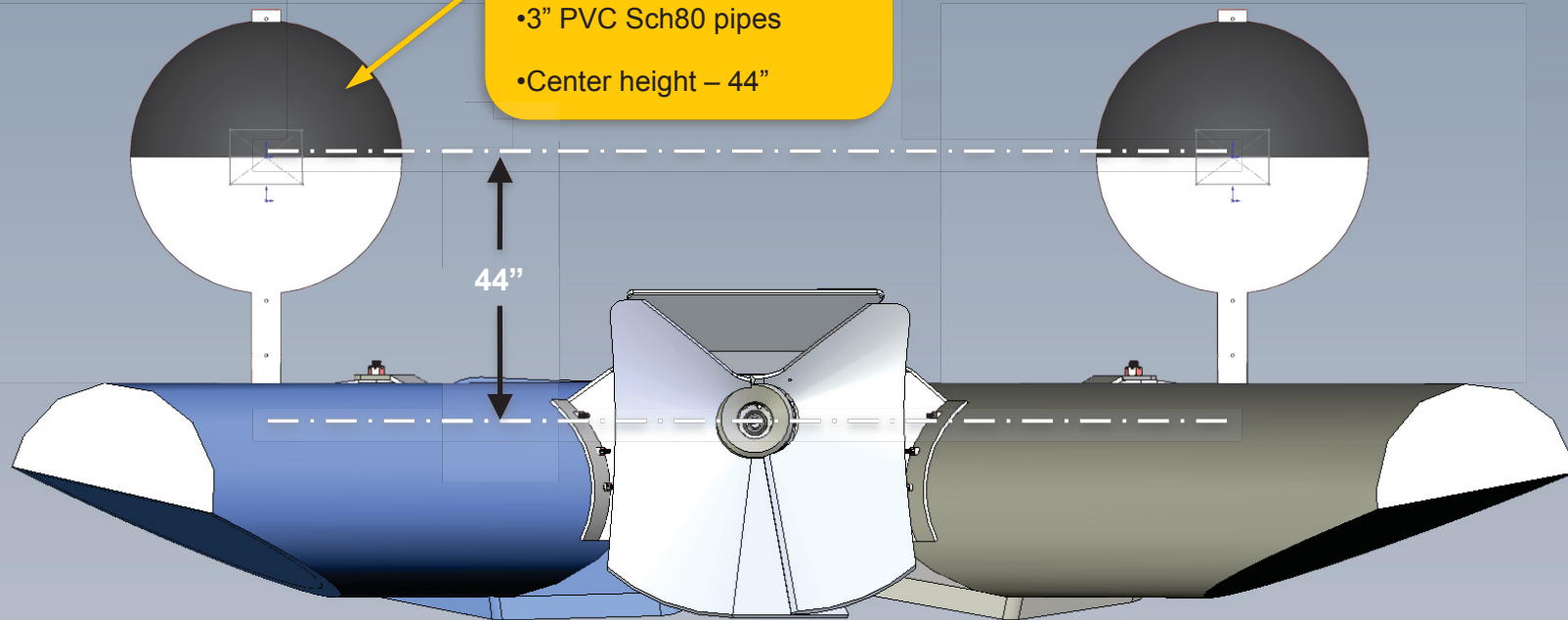
Visual Targets:

• 30" marker buoy

• 3" PVC Sch80 pipes

• Center height – 44"

44"

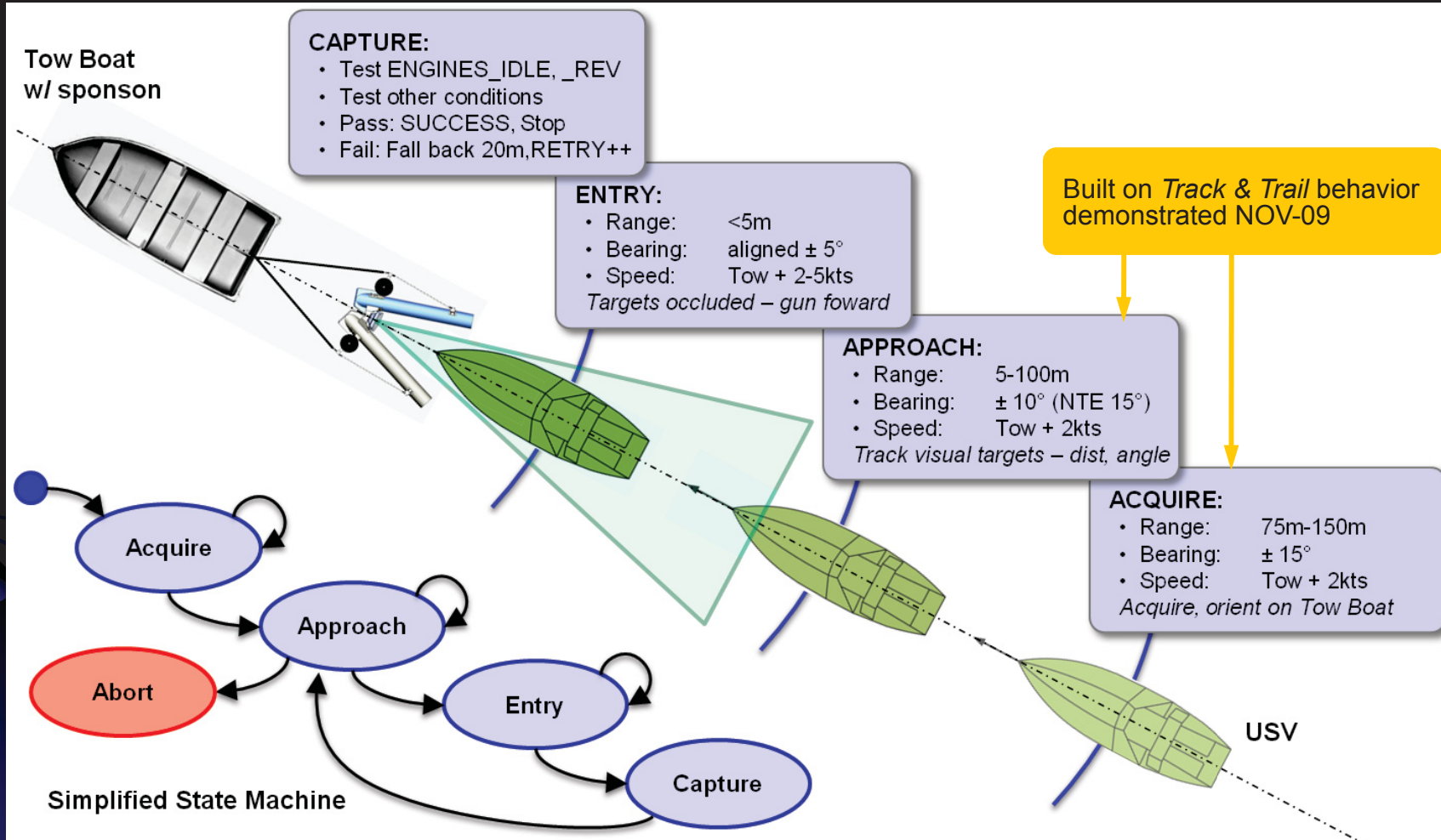Visual targets were added for sponson attitude estimation during docking.

NAVSEA
CARDEROCK

USV Autonomous Docking State Machine

Office of Naval Research

Tow Boat w/ sponson

CAPTURE:
- Test ENGINES_IDLE, _REV
- Test other conditions
- Pass: SUCCESS, Stop
- Fail: Fall back 20m, RETRY++

ENTRY:
- Range: <5m
- Bearing: aligned ± 5°
- Speed: Tow + 2-5kts
Targets occluded – gun foward

Built on *Track & Trail* behavior demonstrated NOV-09

APPROACH:
- Range: 5-100m
- Bearing: ± 10° (NTE 15°)
- Speed: Tow + 2kts
Track visual targets – dist, angle

ACQUIRE:
- Range: 75m-150m
- Bearing: ± 15°
- Speed: Tow + 2kts
Acquire, orient on Tow Boat

USV

Acquire → Approach → Entry → Capture

Abort

Simplified State Machine

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A: Sponson towed by PL. A stable track was observed for this run using the standard stereo algorithm. At this distance, the PL and sponson are lumped together with PL dominating the range return. Additional tracking behavior added to address this and derive approach angle wrt to sponson.
*B: Edge of dock, C: Channel marker.* Frame-to-frame variations cause B & C to have slight, non-zero velocities. Both contacts are classified as navigational hazards based on Electronic Nautical Chart (ENC).

Localization of Fiducial Markers in Stereo Images

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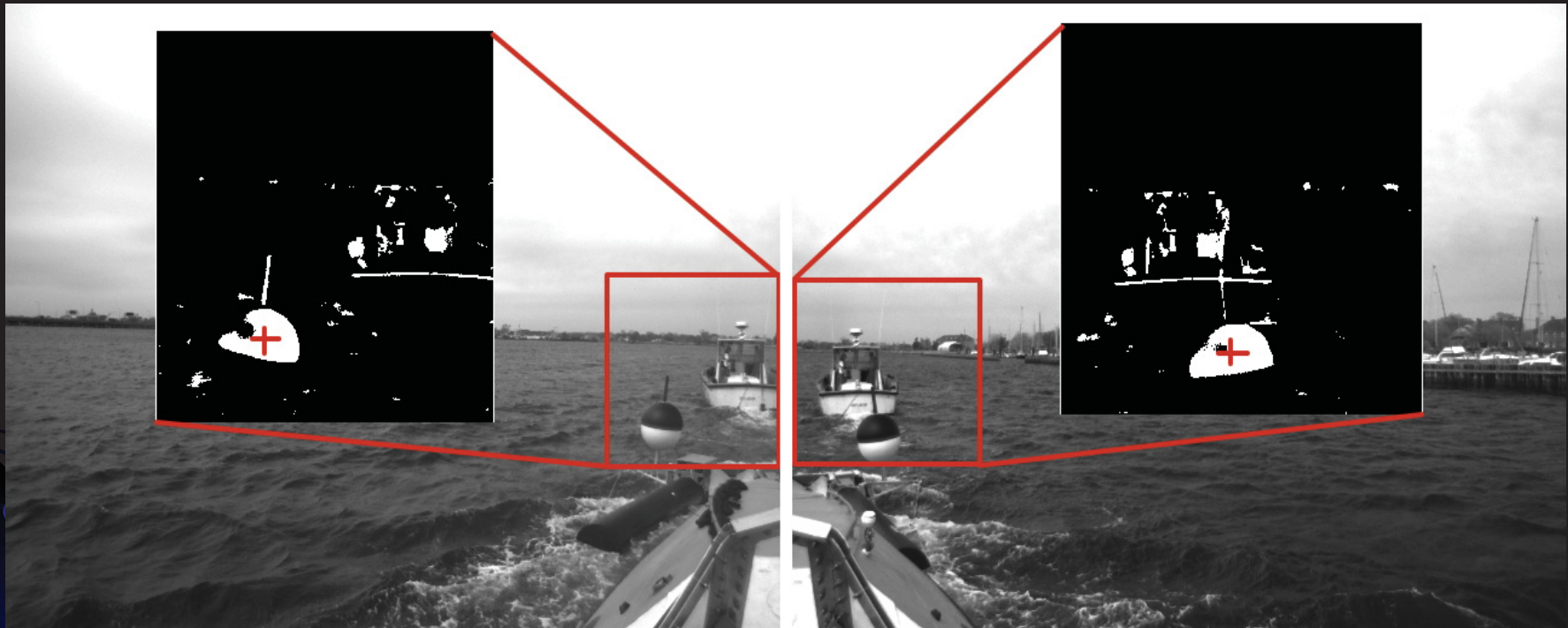
Geometry of sponson is used to estimate velocity and distance to the fiducial markers for USV relative pose estimation and planning for docking trajectory.

Time constraints precluded on-water testing of the docking algorithm during FY'10

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FY11 Efforts

Tasks

COLREGS [Passive Sensors – JPL; Active Sensors – SIS]

- Simulation [JPL] - Completed
- Multi-Boat Data Collection [SIS] - Completed
- At-Sea Testing / Demo [JPL & SIS] – scheduled for MAR 2011
  - Single boat traffic
  - Multi boat traffic
  - Hostile boat
  - High speed operation

Search, Intercept & Inspect – scheduled to start FEB 2011

- RBF Filter development [JPL]
- Tuning with collected data [JPL]
- At-Sea Testing / Demo [JPL & SIS]
  - Type based discrimination for multi intruders
  - Heading and velocity based discrimination

CASPER [JPL & SIS] – scheduled to start MAR 2011

- Development & Simulation
- At-Sea Testing / Demo

COLREGS

COLREGS with multiple boats

- Overtake, Head-on, Crossing
  - Motion planner algorithm development – cost sharing with DARPA ACTUV
  - 360 sensor used for contacts outside the stereo sensing range
- Neutral (straight-line), Friendly (following COLREGS), and Hostile (could violate COLREGS) boats
  - Moving obstacle avoidance algorithm within some threshold
  - Can adjust the problem difficulty (how "hostile" they are)
- High-speed
  - Use the straight-line based path evaluation with larger buffer & PID gain tuning
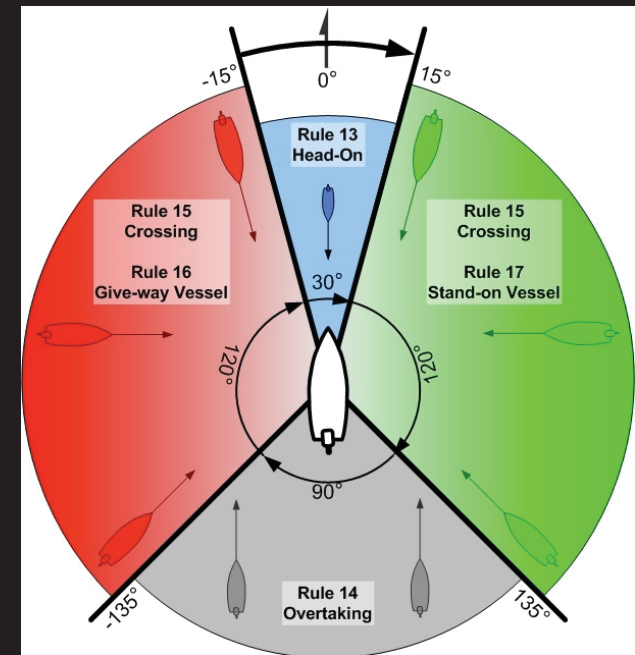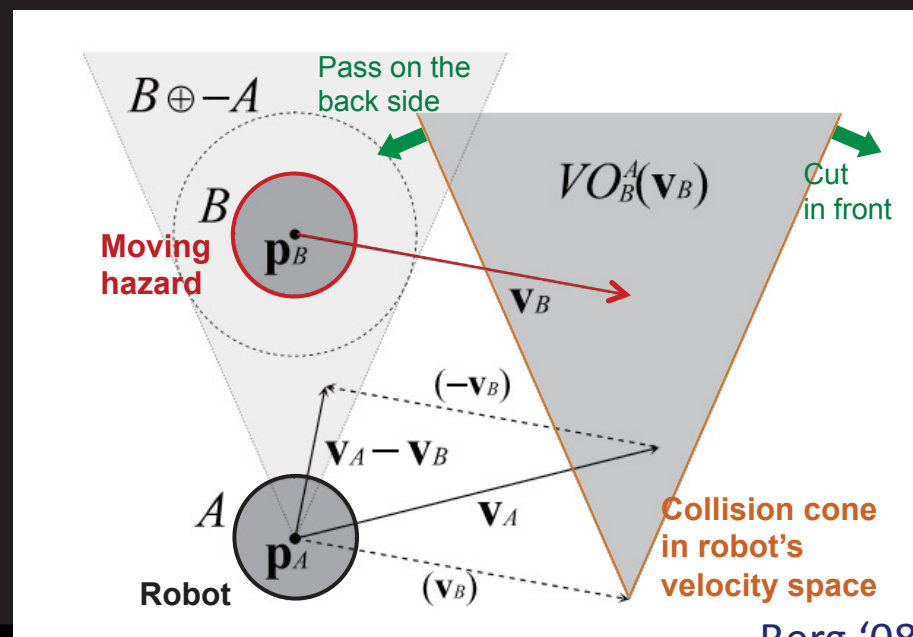
COLREGS Approach

Extension of reciprocal velocity obstacles
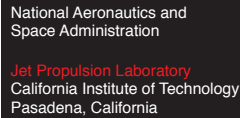
- A cone in velocity space represents collision with a moving hazard
- Determines which side of hazard the avoidance maneuver will pass
  → Can naturally add rule-based constraints such as COLREGS
  (e.g., "do not pass on the starboard if head-on approach")
- Adding general shaped hazards & other manned/unmanned boats
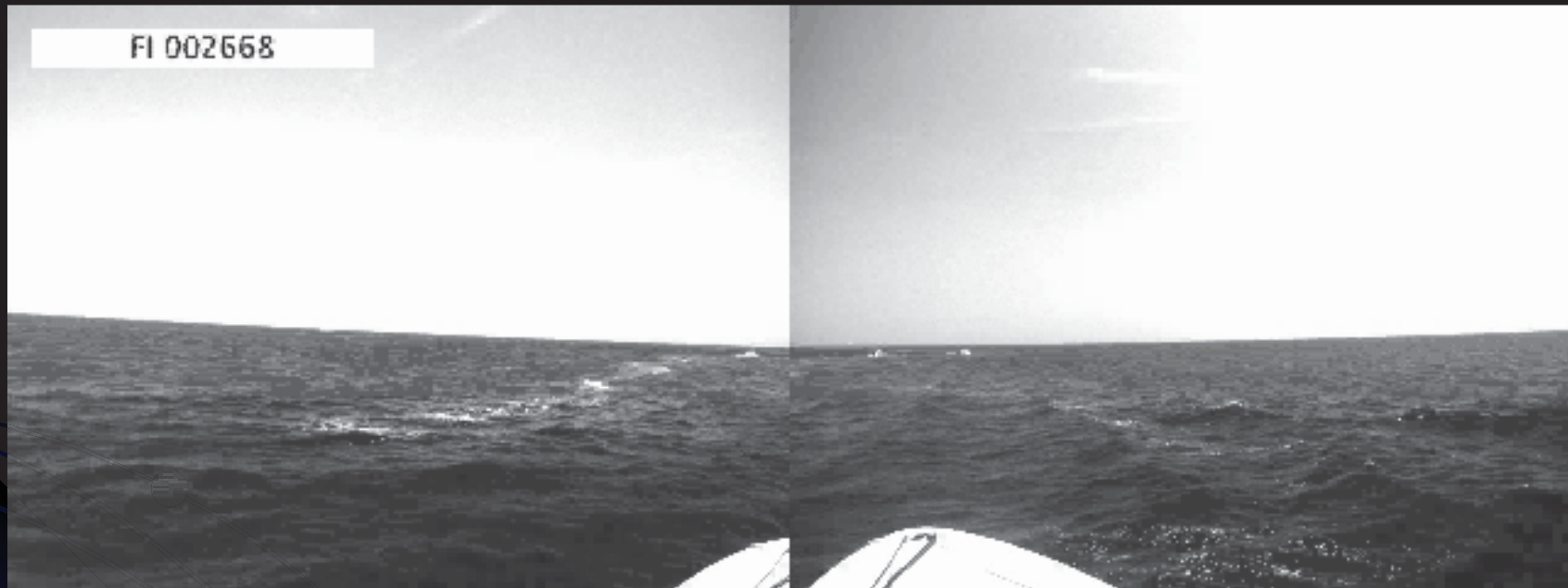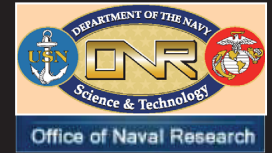- Handling uncertainties

General purpose

- Can handle static hazards
- Multiple COLRES rules/hazards constraints in the decision space
- Use the waypoint-following interface of CARACaS when running on the water

Pass on the back side

$B \oplus -A$

B

$VO_B^A(\mathbf{v}_B)$

Cut in front

Moving hazard

$\mathbf{p}_B$

$\mathbf{v}_B$

$(-\mathbf{v}_B)$

$\mathbf{v}_A - \mathbf{v}_B$

A

$\mathbf{v}_A$

Collision cone in robot's velocity space

$\mathbf{p}_A$

$(\mathbf{v}_B)$

Robot

Berg '08 ICRA

FI 002668

Real-Time Code Simulation Overtake & Head-On
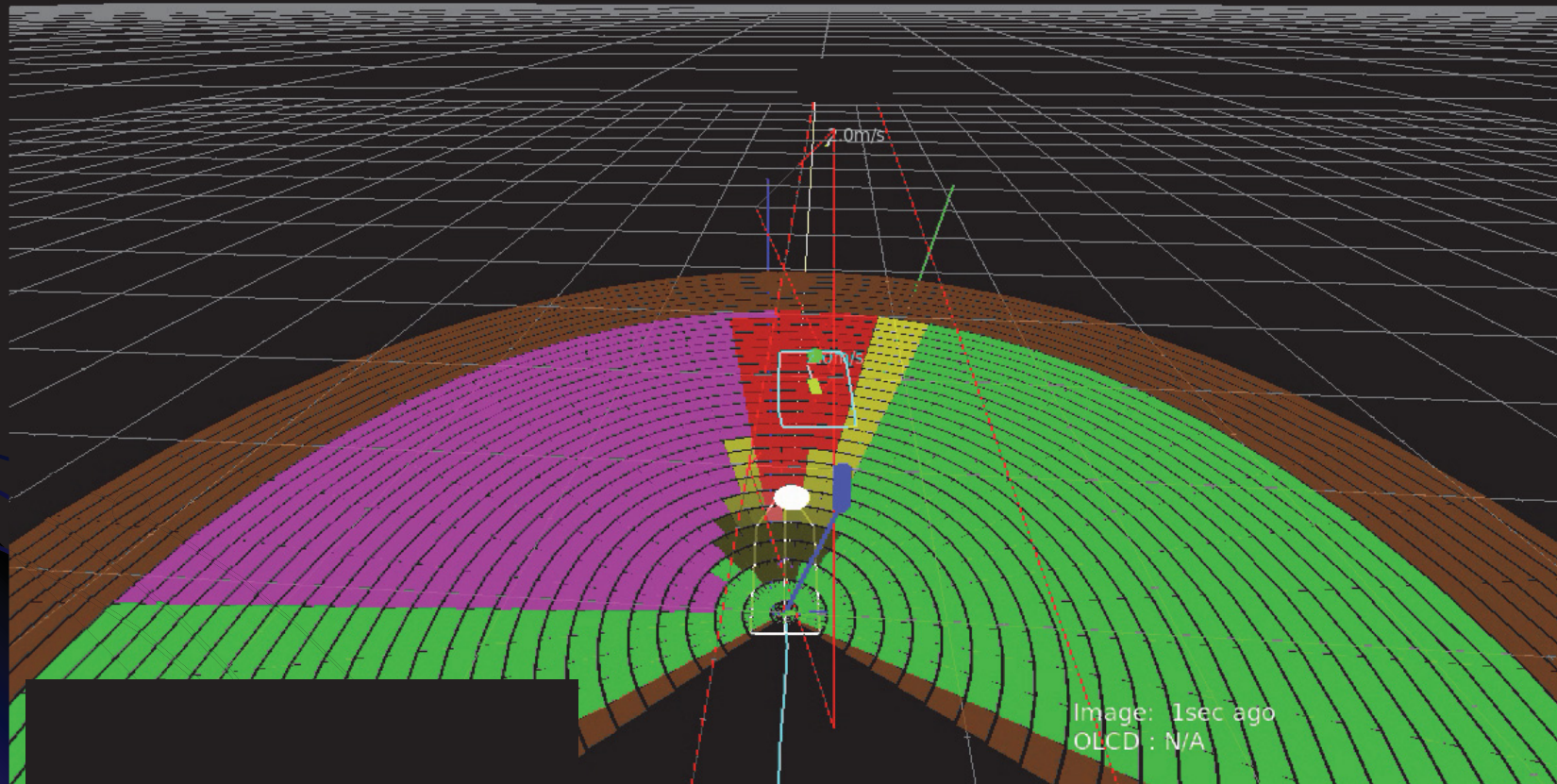
COLREGS Constraint   Clear   Hazard   Safety Buffer

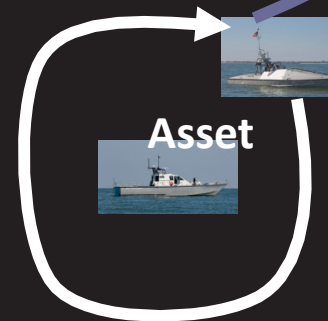# Real-Time Code Simulation Crossing
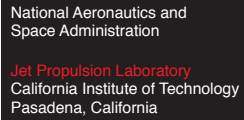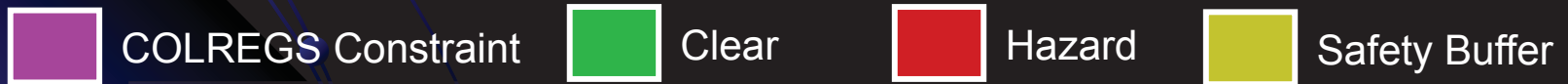
Intercept

Search, Intercept, and Inspect with multiple contacts

- FY'09 demo
  - Hand-off from 360 to stereo
- Similar scenario with multiple contacts

Intruder

Asset

- Contact discrimination
  - Type-based (flag PL but not 7m RHIB)
  - Bearing-based (select the one with erratic trajectory)
  - Distance-based [stretch goal]
  - Speed-based [stretch goal]

CASPER

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Additional **faults** / more comprehensive **response plans**

- Use actual readings of **fuel level** and re-plan (e.g., add activities / waypoints)
  - Simple version done in FEB 2006 with spoofed data
- If **engine temperature** too high, slow down & drop waypoints
  - Simple version done in FEB 2006 (very canned response)
  - Want to reason about the planned route & guide what to drop
  - Use other factors (e.g., priorities on waypoints) to guide re-planning – based on FY'10 demo
- If a **stereo camera** goes off-line, maneuver differently to accommodate the limited FOV
- Based on **situation**, automatically adjust velocity
  - e.g., boost speed to ensure a later activity could be reached or deadline made
  - Reason about goal priorities and how much fuel consumption could be allowed on vehicle for high priority activities.

Summary

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- On-water demonstration of a wide range of **mission-proven, advanced technologies at TRL 5+** that provide a **total integrated, modular approach** to effectively address the majority of the key needs for **full mission-level autonomous, cross-platform control** of USV's.

- **Wide baseline stereo system** mounted on the ONR USSV was shown to be an effective sensing modality for **tracking of dynamic contacts as a first step to automated retrieval operations.**

- CASPER **onboard planner/replanner** successfully demonstrated **real-time, on-water resource-based analysis** for mission-level goal achievement and on-the-fly opportunistic replanning.

- Full **mixed mode autonomy** was demonstrated on-water with a **seamless transition** between operator over-ride and return to current mission plan.

- **Autonomous cooperative operations** for fixed asset protection and High Value Unit escort using 2 USVs (AMN1 & 14m RHIB) were demonstrated during **Trident Warrior 2010** in JUN 2010.
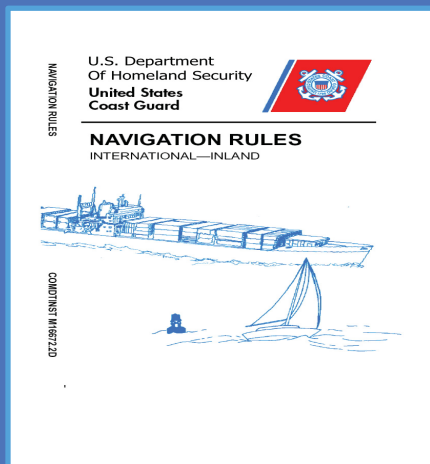
Questions?

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